Quaternary Science Reviews 30 (2011) 2107–2123

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Late-Pleistocene (MIS 3-2) palaeoenvironments as recorded by sediments, palaeosols, and ground-squirrel nests at Duvanny Yar, Kolyma lowland, northeast Siberia

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ARTICLE INFO

Article history:
Received 31 October 2009
Received in revised form
19 January 2011
Accepted 22 January 2011
Available online 8 March 2011

Keywords:
Late Pleistocene
Kolyma lowland
Paleosols
Fossil rodent burrows
Palynomorphs
Plant macrofossils
Insect

ABSTRACT

A detailed study of the Duvanny Yar section in the Kolyma Lowland (Yakutia) provides the most extensive knowledge to date about late-Pleistocene soil formation processes and environments in the North–East Siberian Arctic. Late-Quaternary palaeoenvironmental changes were reconstructed using paleopedological data and a range of palaeoecological bio-indicators (palynomorphs, plant macrofossils and insects). The frozen sediments representing marine isotope stage 3 (MIS-3), which encompasses the Karginsky interstadial, include profiles of four palaeosols of different ages. The oldest palaeosol is early Karginskian, and three overlying soil horizons represent a late-Karginskian pedocomplex. Palaeopedological data indicate a change of from synlithogenic soil formation processes to epigenic ones during these intervals. The intervening periods of synlithogenic pedogenesis were accompanied by active accumulation of eolian deposits. The Earlier Karginskian period of pedogenesis occurred in the absence of eolian sedimentation and when summer conditions were warm. The wide spectrum of peaty and peaty-gley soils observed in the late-Karginskian deposits developed under conditions of progressive cooling. The structure and content of fossil rodent burrows dated to approximately 30 000 yr BP from frozen late-Pleistocene deposits at Duvanny Yar indicate an arid and severe climate, a depth of active layer of 60–80 cm, and a wide distribution of disturbed habitats with pioneer and steppe vegetation.

1. Introduction

Palaeopedological investigations of the *Yedoma*, or "ice complex"—extensive frozen, silt-dominated deposits characterizing the arctic lowlands of northeast Siberia—began 30 years ago (Gubin, 1984), although the presence of pedogenic indicators in the sediments had been observed earlier. Many field workers noted the presence of prominent organic layers in Yedoma, and some suggested these were buried soil profiles (e.g., Kaplina and Sher, 1977; Sher et al., 1979; Bolikhovskaya and Bolikhovsky, 1979; Tomirdiaro, 1980; Kaplina and Giterman, 1983; Tomirdiaro and Chernenky, 1987). Gubin (1984) developed concepts of soil formation within the ice complex under periglacial conditions. Synlithogenetic soil formation occurs when parent materials are transformed by pedogenetic processes but there is an absence of soil profile formation due to continual deposition of aeolian silt on the land surface. In such soils concentrations of organic material are low and other soil properties are weakly developed. Epigenetic soil formation refers to processes where differentiation of the active layer material takes place in genetic horizons and soil profiles develop. Gubin (1994, 1997, 1998, 2002) established the presence of multiple epigenetic soils in the Duvanny Yar exposure that relate to MIS-3 (Gubin, 1994, 1997).

In this study we examine the palaeoenvironmental record preserved in the frozen palaeosols of the Duvanny Yar site. This research includes observations from 1979 to 2009, led by S. Gubin. Objectives were i) to describe palaeosols, ii) to collect fossil ground-squirrel nests which contain well preserved plant fossils (including viable seeds) and animal remains (including soft tissue of rodents and insects), and iii) to estimate the viability of organisms preserved in frozen sediments and their potential role in the development of the modern biota. Previous studies demonstrate the viability, using *in vitro* plant tissue culture, of seeds and fruits of *Silene*, *Arctous* and *Polygonum* (Yashina et al., 2002).

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doi:10.1016/j.quascirev.2011.01.021

Duvanny Yar is one of the best known Quaternary sites in west Beringia. It is located in the Kolyma Lowland in what is now the eastern coastal plain of Yakutia. The Duvanny Yar section was first described by Baranova (1957) and Biske (1957), who showed that the outcrop included Ice Complex sediments and a lower unit that accumulated earlier in the Pleistocene. The Duvanny Yar outcrop was subsequently investigated by several researchers (Sher, 1971; Kaplina and Kuznetsova, 1975; Kaplina et al., 1978; Tomirdiaro, 1980; Kaplina, 1981; Konishev, 1983; Gubin, 1984; Tomirdiaro and Chernenky, 1987; Sher and Plakht, 1988). During glacial periods, this area was far from the ocean and its climate was affected by the Siberian anticyclone; data suggest that the climate was strongly continental, probably more so than in other parts of Beringia, and biotic indicators record the dominance of tundra-steppe communities in the region (Alfimov and Berman, 2001; Kiselev, 1981; Kuzmina, 2003).

The Duvanny Yar locality contains Late Pleistocene and Holocene deposits. The outcrop itself is an extremely ice-rich river bluff; it constantly changes during the summer due to thaw, new exposures appearing as old ones become covered. The locality has been the subject of many past investigations, and work continues today. Our research was focused on deposits from MIS stage 3 (ca 26–50 ka BP, known in the Russian Arctic as the Karginsky interstadial) and MIS-2 (the Sartan stadial; 10–26 ka BP). The Pleistocene section is comprised of Yedoma, a specific unit of deposition variously termed Yedoma Series, Yedoma Suite, and Yedoma Complex (Sher, 1997). *Yedoma* is often used as a synonym for Ice Complex or ice-loess formation; Bolikhovskaya (1995), for example, proposed that Yedoma is a syncryogenic analogue of loess formation. Generally Yedoma is dominated by sand and silt grain sizes, either sorted or massive, and it is usually rich in plant, insect and vertebrate fossils. Large ice wedges are a prominent feature. Such sediments, or facies of similar grain size (though with varying ice content), occur elsewhere in Yakutia (on Arctic islands, coastal lowlands, and in the central region), in western Siberia, in the Anadyr River basin (Chukotka), and in Alaska and Canada. The origin of Yedoma is still debated, and includes eolian (Tomirdiaro, 1980, 1982; Tomirdiaro and Chernen'ky, 1987), alluvial (Popov, 1953) and polygenetic origins (Konishev, 1975, 1983; Zhestkova et al., 1986; Sher, 1997). The last hypothesis is most common among Russian scientists, as it allows for a generally eolian origin while including different genetic horizons: alluvial, lacustrine, allochtonous peat and *alasses* (drained thaw-lake basins).

Duvanny Yar is the key section of Late-Pleistocene sediments in the Kolyma Lowland. In Russian studies it is the stratotype of the Yedoma Suite (Vaskovsky, 1963). The term "Duvanny Yar Interval" (ca 25 000–14 000 yr B P) is used by western scientists (Harington, 1978; Hopkins, 1982), but this term is not commonly used in Russia, where the name "Alyoshkin Suite" is used (Sher, 1971; Sher et al., 1979). Radiocarbon data from Duvanny Yar indicate that the Pleistocene unit formed from 53 000 to 10 000 years ago (Tomirdiaro et al., 1984; Vasilchuk, 1992; Gubin, 1999; Sulerzhitsky and Romanenko, 1997; Vasilchuk et al., 1988). For many years, Andrei Sher and his colleagues paid special attention to this section. Duvanny Yar has been included in programs of international field excursions (e.g., Sher et al., 1979) and collaborations (e.g., Eisner and Ping, 1995; Igarashi et al., 1995).

This paper provides a review of the work carried out on Duvanny Yar palaeosols and summarizes both published and previously unpublished information. Building on the initial work of Gubin (1984), we review the characteristics, origins and palaeoenvironmental significance of the palaeosols and make a palaeoenvironmental reconstruction based mainly on the palaeosols. Special emphasis has been placed on chemical properties, morphological, palynological and palaeoentomological data, and the remains associated with ground-squirrel nests.

2. Regional setting

The Kolyma lowland is the part of the Maritime Lowland that characterizes the Arctic Ocean coast. Spurs of the North Anyuy range and the Yukagir plateau border it to the east and the Ulakhan-Sys ridge borders it to the west. The relief is dominated by low hills (50–100 m ASL), and there are traces of several levels of sediment accumulation, but these are heavily obscured by widespread thermokarst. Polygons, frost cracks, pingos, thermokarst pits, alasses and baidzherakhs (inter-wedge sediment mounds) reflect cryogenic processes. Today much of the region is covered by northern boreal forest zone dominated by larch (*Larix dahurica*), which gives way to coastal tundra near the Arctic Ocean coast.

2.1. The Duvanny Yar section

The Duvanny Yar exposure is located in the right hand Kolyma river bank (Fig. 1); 68° 37′ 739″N, 159° 11′ 678″ E. and is set within a typical Yedoma landscape. The outcrop is about 9 km long and up to 55 m high. Seven gentle domes of loess-like sediment and four bisected Holocene thermokarst lakes (alasses) can be distinguished (Sher et al., 1979).

The main unit (Yedoma) consists of syngenetic bluish-grey or grey-brown silt with large ice wedges up to 6–8 m wide and up to 30–40 m high. These ice wedges divide a bluff into separate mineral blocks (Fig. 2A and B). An older unit, characterized by lacustrine deposits, lies near river level. Sher et al. (1979) and Vasilchuk (1992) ascribe the lower part of the Yedoma to MIS-3. The colour varies from bluish-grey (10YR5/1) to brownish-grey (10Y5/3) and is evidently controlled by the amount of organic matter present. Much of the sediment also contains thin roots of herbaceous plants and is characterized by thin ice lenses or reticulate cryostructures. There are also sandy alluvial layers with lenses of in-washed detritus and rounded mollusc shells, peat layers with fresh-water molluscs, and peat with twigs of shrubs and other woody macrofossils.

A peat layer and three buried soil profiles of differing age are clearly identifiable. Most burrows are found between palaeosol II and III. Just above palaeosol III lie massive silts associated with MIS-2, and no palaeosols are present. The top of the Yedoma unit was eroded by thermokarst in the early Holocene. The Holocene unit contains layers of ice-rich material with ataxitic cryostructures. Ice content may reach 80% of sediment volume in these

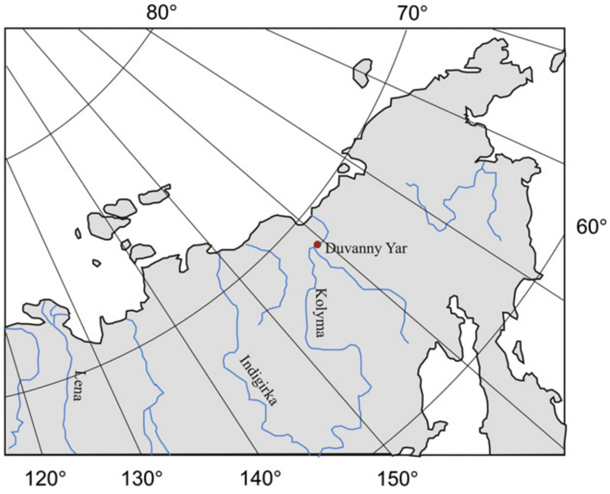

Fig. 1. Location of Duvanny Yar on the Kolyma River, eastern Siberia.

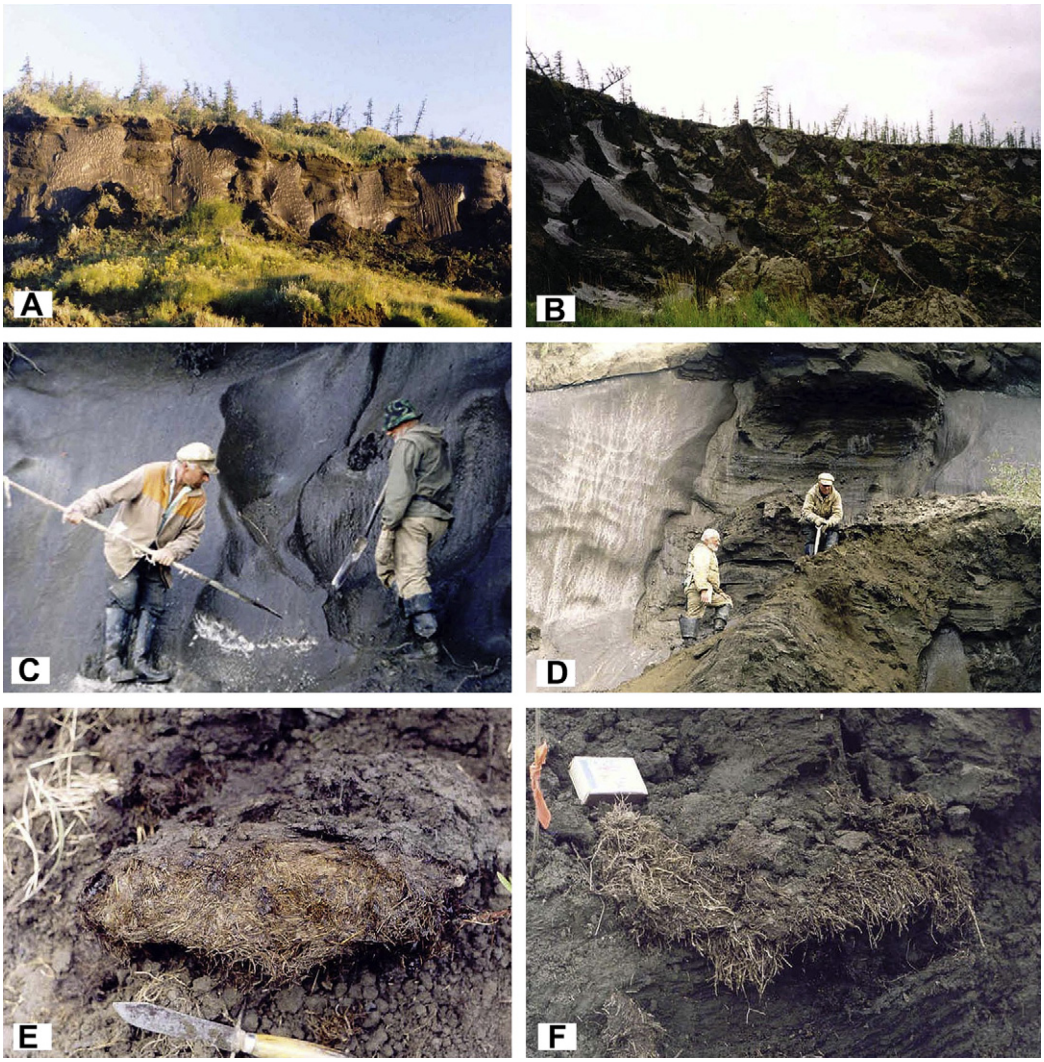

Fig. 2. Photographs of the Duvanny Yar exposure: A, and B - general views: A – lower (MIS-3) showing baidzherakhs and ice wedges in the outcrop VI (photo of summer 2002), B – upper (MIS-2) showing a series of baidzherakhs; C – layer with fossil rodent burrows; D –Late-Karginskian palaeosol II in outcrop VII; E, F - fossil burrows with herbaceous litter from MIS-3 cryopedolith.

sediments (Fig. 2A). Holocene deposits up to 2.5–3 m thick and modern soils (up to 70 cm) form the topmost part of the exposure.

3. Materials and methods

3.1. Palaeopedologycal and cryolithological analysis

Several profiles that included the Yedoma silt (synlithogenetic pedogenesis), epigenetic palaeosols, allochthonous and autochthonous peat layers, and alluvial layers were sampled across the section. Palaeosols and associated sediments from different places on the outcrop were described and sampled in different years. Morphological descriptions (Fig. 5.) used soil horizon designations according to the WRB classification (FAO, 2006). Samples for physical and chemical characterization were taken using a knife or axe from freshly cleaned faces of sections. The samples were dried at room temperature prior to analysis.

In order to classify the palaeosols with respect to modern soils we undertook the following analyses. Loss-on-ignition of water-soluble mineral salts was determined by burning of soil aqueous extract at 600 °C in a muffle furnace. Exchangeable cations (Ca, Mg, Na, K) were determined by extraction with 2N NaCl. Soil organic carbon (SOC) was determined by heating with $Cr_2\ O_7 + H_2SO_4$. CaCO3 equivalent was determined by the gravimetric method. Extractable Fe was determined by Tamm's extraction using $(NH_4)_2C_2O_4{\cdot}H_20$, pH 3.2, and available soluble forms of phosphorus and potassium by Kirsanov's extraction with 0.2N HCl. For pH we used a soil: water suspension in a 1:2.5 ratio and a 1M KCl solution with a Mettler TALEDO–Seven Easy pH meter.

3.2. Palaeoecological analyses

A range of palaeoecological analyses provides new information on the environment under which soil formation occurred. Pollen and spores were studied by DL, plant macrofossils by SVM, and fossil insects by SK. Samples for plant macrofossil analysis were taken from frozen cryopedoliths, palaeosols and fossil arctic ground-squirrel burrows (chambers and entrance tunnels). The best preservation of plant macrofossils typically occurs in fossil rodent burrows, where burial and freezing occur fastest. The samples of palaeosols and sediments were thawed, screened through sieves with mesh size of 0.25 mm, and air-dried in the field. Good preservation of seeds allowed identification to species level, using collections of modern seeds in the St. Petersburg

Botanical Garden and modern seeds collected by SVM. Classification of vascular plants was taken from Cherepanov (1995), mosses from Savich-Lyubitskaya and Smirnova (1970) and lichens from Golubkova (1966). Ecological interpretations are based on the guide to Yakutia higher plants (Tolmachev, 1974).

Palynological studies have been carried out previously on Duvanny Yar sections (Kaplina et al., 1978; Sher et al., 1979; Giterman et al., 1968; Lozhkin, 1984; Giterman, 1985; Vasilchuk et al., 1988; Nikolskaya et al., 1989), but these studies were not as detailed as the one presented here. More than a hundred pollen samples were taken from a range of horizons including epigenetic palaeosols, cryopedolithic silt units, zones of contact between units, and fossil burrows and surrounding material. Pollen and palynomorphs were studied following the method of V.P. Grichuk (e.g. Krishtofovich, 1950; Pokrovskaya, 1966). Pollen and spore types were indentified and counted using a compound microscope with 400x and 600x magnification, to at least 200 pollen grains or spores. Percentages of pollen taxa were calculated based on the pollen sum, and percentages of spore-producing taxa were based on the total number of spores. For any group with fewer than 50 grains total, percentages of taxa were calculated.

Many fossil insects from permafrost deposits of northeastern Asia are Coleoptera (beetles), but Hemiptera (true bugs), Hymenoptera (bees, wasps) and Diptera (flies) are also present (Kiselev, 1981). Sampling and laboratory processing for insects follow Sher and Kuzmina (2007).

3.3. *Analyses of fossil burrows*

The fossil nests in the Ice Complex deposits preserve species from plant communities that occupied the surface at the time the burrows were occupied. The variety of remains in fossil nests stimulated a special search for burrows in the Duvanny Yar section (Fig. 2C, E and F). They were first discovered in Yedoma by Gubin and Khasanov (1996) and subsequently described from cryopedolithic layers (Gubin et al., 2001, 2003; Zanina, 2003, 2005). The most common burrows were made by arctic ground squirrels, *Spermophylus parryi* (Rich.). They contain organic matter in excellent condition, including seeds, fruits, twigs, stems and leaves, moss and lichen parts, insects, eggshells, feathers, excrement, and the bones, hair and tissues of mammals.

The frozen material thawed and dried layer by layer during the field investigation. About 0.1 kg of each sample was dry-sieved through 0.50-mm and 0.25-mm mesh screens to separate organic and mineral parts of materials. The material retrieved from the 0.25-mm sieve was used for palynological analysis. Wet-sieving was avoided as it tended to damage material. Fossil insects from rodent burrows were limited by the small volume of the burrows, but excellent preservation makes these samples informative.

3.4. *Radiocarbon age of sediment, palaeosols and fossil burrows*

The age of the palaeosols and other sediments is based on stratigraphy and radiocarbon dating. The first of a number of radiocarbon dates from Duvanny Yar sediments were obtained more than 30 years ago (Kaplina et al., 1978,Sher et al., 1979; Gubin, 1984,Tomirdiaro et al., 1984; Vasilchuk, 1992; Sulerzhitsky and Romanenko, 1997; Vasilchuk et al., 1988). In this study material for radiocarbon dating of palaeosols was obtained from frozen horizons that had higher concentrations of organic matter and from plant remains, bones and organic material from burrows (date information and stratigraphic position are given in Fig. 3). Samples were thawed, dried, and brought to the laboratory, where the soil organic matter fraction was extracted using NaOH. The radiocarbon measurements were conducted at the Laboratory of Isotope Geochemistry and Geochronology of the Geological Institute (GIN), Russian Academy of Sciences. One sample of buried organic materials collected from rodent burrows was submitted for radiocarbon dating by accelerator mass spectrometry (Beta Analytic). In the lower part of the section oldest dates are about 50 ka BP and should be treated as minimum ages.

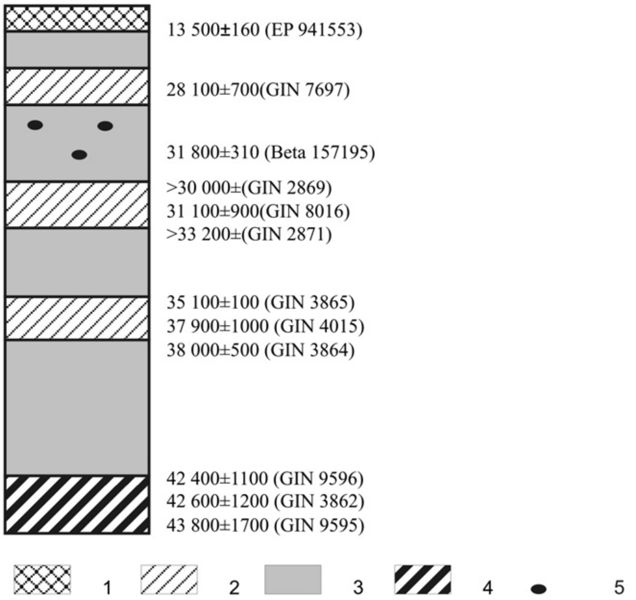

Fig. 3. General geological scheme (not to scale) plus radiocarbon data from the Duvanny Yar sections. Key: 1-modern soil and cover layer; 2-palaeosols; 3-cryopedolith; 4 – Early Karginskian peat; 5- fossil burrow.

4. Results

The most extensive study of the Duvanny Yar section was made on so-called outcrop VI (Fig. 2A). Kaplina et al. (1978) produced a descriptive scheme for this section. It has been visited 15 times in the last 25 years, and over this period the top and middle parts of the bluff have been eroded back more than 60 m by thawing, revealing new features and allowing horizontal, as well as vertical reconstructions. We recognize four palaeosols (with specific genetic horizons) of different ages (Fig. 2D).

4.1. *MIS-3 deposits*

The deposits we studied overlie an older unit with peat and ice wedge casts (Kaplina et al., 1978), dating to more than 45 ka BP, but this unit was covered and inaccessible. MIS-3 deposits are primarily cryopedolith; a peat layer and three soil profiles are present and may be replaced by alluvial deposits (peaty sands) across the section. The MIS-3 cryopedolith layers are similar to the MIS-2 cryopedoliths in their basic chemical features, structure and color (see below). They differ by slightly higher concentrations of soil organic carbon (SOC) (1.5% by average, $n = 26$; Table 1). Significant differences are observed for the brownish (10YR5/3) cryopedolith layers: an increase in SOC concentration and loss-on-ignition, and higher C/N ratios. Micromorphological analysis shows an increase of moss as in the organic material.

4.2. *Early Karginskian peat*

A histosol in the lower MIS-3 unit of the VII outlier is described as 9–11 m above river level (Kaplina et al., 1978). Autochthonous

Table 1
Chemical properties of cryopedolith MIS 2.

Lab.No	Depth, m	Ignition losses, %	Organic C %	pH		Exchangeable bases, mg-eq/100 g soi					Avaliable forms		Carbonate CO_2, %	Oxalate exractable, %	
				Water extraction	KCL extraction	Ca	Mg	Na	K	$\sum$	P_2O_5 mg/100 g soil	K_2O_5, mg/100 g soil		Fe_2O_3	Al_2O_3
1018	3.3	6.12	1.20	8.2	7.5	19.6	9.3	1.0	0.3	30.2	51.8	8.4	0.86	0.64	0.42
	5.5	6.24	1.08	8.3	7.6	20.7	10.3	1.4	0.2	32.0	53.6	6.1	0.86	0.54	0.36
	9.0	5.48	0.61	7.5	7.0	14.7	9.4	0.9	0.4	25.4	57.1	6.3	0.98	0.84	0.28
	11.4	7.81	1.42	7.9	7.6	16.4	8.1	1.0	0.3	25.8	50.6	5.6	0.61	1.14	0.47
	14.0	6.44	1.34	8.0	7.7	21.1	6.0	0.8	0.4	28.3	61.7	4.8	0.37	1.02	0.51
	18.1	6.0	0.60	8.2	7.7	19.6	6.4	0.8	0.3	27.1	44.1	6.1	0.86	1.14	0.61
	18.4	12.9	2.80	8.4	7.5	20.8	7.1	0.6	0.3	28.8	51.4	5.8	0.86	1.64	0.71
	18.6	7.8	1.20	8.3	7.7	19.1	7.2	0.4	0.3	27.0	55.3	4.6	0.64	1.27	0.45
	18.8	8.3	1.20	8.4	7.5	18.4	6.0	0.4	0.3	25.1	51.0	4.5	0.86	1.27	0.45

peat layers up to 1.5 m thick overlie lacustrine deposits. Radiocarbon dating gives an age of 40 000–43 000 yr BP (Fig. 3). This horizon is considered an Early Karginskian peat, formed by active pedogenetic processes under a warm and moist climate.

Macrofossil records from the peat layers show change over time. The initial phases indicate poorly-drained conditions with dwarf willow-sedge-horsetail vegetation. Subsequently *Sphagnum* mosses, sedges and *Comarum palustre* dominated, and lenses of *Polytrichum* sp., sedges, grasses, and willows occur. *Larix* trunks in the upper part of the horizon indicate forest vegetation. Pollen from the peat indicates an open larch forest with alder, dwarf birch and willow. The epigenetic ice wedges associated with the peat suggest a polygonal ground network and hence probably a mosaic of plant communities.

We did not sample this unit for insects. Earlier studies by S. Kiselev (1981), record the presence of the xerophilous steppe-tundra pill beetle, *Morychus viridis*, and the steppe weevil, *Stephanocleonus eruditus*, was also present. The assemblages indicate a steppe-tundra environment.

In other parts of the section (outliers II and III) this horizon is represented by allochthonous peat layers (about 0.6 m). This is a silty peat with some sand, and contains remains of sedge, *Sphagnum*, twigs and herbaceous detritus. These deposits include abundant minerals in the silt fraction. The main feature of this peat layer is an abundance of woody birch macrofossils and large branches of other arboreal taxa (willow and alder). These observations suggest accumulation of the unit while trees were present on this surface or nearby, but this is not consistent with the insect data.

4.3. Late-Karginskian soil complex

Three buried soil profiles from the MIS-3 part of the section are well expressed at site V (faces E and F) and VII (face A) (Fig. 4). However, a lengthy exposure at site V (over 1.0 km) shows complexity, with indications of a dynamic landscape during soil formation periods. The complexes are named I, II and III, respectively.

4.3.1. Late-Karginskian palaeosol I (I LKP)

A palaeogleysol is present 10–15 m above river level and includes peat horizons and buried tussocks. The palaeosol is underlain by ice-rich loam. Profile thickness is up to 2 m (Fig. 5) with ice content (up to 80%) in the middle and lower parts of the section. Taking into account the ice content, initial profiles likely did not exceed 1.2 m. Tussocks penetrate the profile to a depth of 0.6 m. This suggests that during soil formation there was a slow rate of mineral deposition. The upper part of the profile consists of a mixture of silt and coarse organic matter with remains of mosses, sedges, grasses and woody plants (willow, dwarf birch, larch) that suggest a shrub-dominated landscape with scattered trees. Radiocarbon dates on plant macrofossils from the upper soil give ages of 35–38 000 years B.P. (Fig. 3).

In the central part of site VI (face D) the buried soils are replaced by 2.5–3 m of allochthonous peat. This peat contains the greatest concentration of large branches, but these show evidence of long distance transport; they are >40 000 yrs old and are hence probably reworked older material.

Soil organic carbon in the upper part of the soil profiles is 3% by weight (8–10% loss-on-ignition) and gradually decreases with depth. Soils have a pH 6.5–6.1 and low ionic concentrations. Micromorphological analysis confirms weak decomposition of organic material in the upper horizons, input of silt during formation and the presence of a mull-type humus in the lower parts of the profiles.

In I LKP herb pollen reaches 32–58%, arboreal pollen 13–41%, and spores 18–45%; Fig. 6. Poaceae dominates the herb pollen, and there are appreciable quantities of Cyperaceae, *Artemisia*, Asteraceae, Ericaceae, and Leguminosae. Arboreal pollen is dominated by *Pinus* subgenus *Haploxylon*, *Betula nana* and *Alnaster*. Spores of *Bryales* (27–57%), *Selaginella rupestris*, *Lycopodium*, and Polypodiaceae are frequent, with *Equisetum* and *Sphagnum* spores also present. In the peaty horizons, (Fig. 6, 1332 [H] and 1332 [ABg]) *Salix* pollen dominates. A grouping of Onagraceae, *Typha*, *Valeriana capitata*, *Betula pubescens,* sedges and mosses suggests margins of tundra bogs. Overall, the pollen spectra indicate largely treeless tundra vegetation, with moist habitats supporting dwarf shrubs.

Macrofossils were collected from two palaeosol profiles (P-1310 and P-1332) in I LKP. The record shows a change from wet bog conditions to an open larch forest with willow. The seeds of the hummock-forming sedges *Carex juncella* and *Carex appendiculata* were found in abundance in the lower levels but were rare in the upper levels. Macrofossils in the upper horizons indicate larch forest; moist habitats are indicated by *Carex concolor.*

The fossil beetle assemblage (Table 2, P- 1332) includes mostly mesic tundra species such as the ground beetles Poecilus (Derus) nearcticus, Pterostichus (Cryobius) ventricosus, P. (Cryobius) pinguedineus, P. (Petrophilus) abnormis, P. (Tundraphilus) sublaevis, Curtonotus alpinus, C. bokori, the rove beetle *Tachinus brevipennis*, the weevils *Mesotrichapion wrangelianum, Coniocleonus zherichini, Hypera ornata,* and *H. diversipunctata* (Fig. 7). Insects typical of steppe-like habitats are uncommon and steppe-tundra indicators are rare. A single individual was found of the death-watch beetle *Caenocara bovistae*, which is more typical of the forest zone.

4.3.2. Late-Karginskian palaeosol II (II LKP)

This palaeosol is located from 18 to 28 m above river water level and is well exposed at outcrops IV and VII, where the soil is gleyed with thin peaty horizons (Fig. 5). Throughout the section the soil

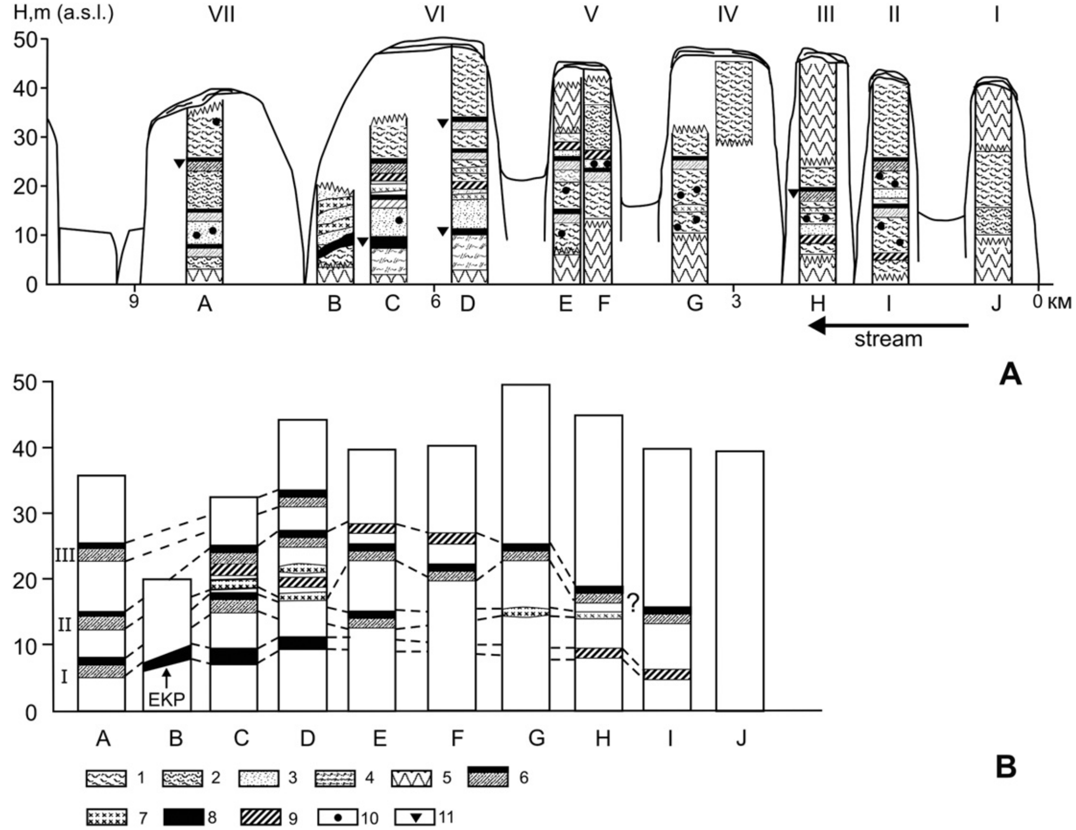

Fig. 4. Schematic diagram showing vertical profiles and palaeopedological units of the Duvanny Yar exposure: A – longitudinal extent, showing eight main outcrops (I-VIII) and cleared faces (A–J); B – correlations of palaeosols and layers with pedogenenic features. Key: 1-cryopedolith; 2-sandy cryopedolith; 3- sand; 4- loam; 5-covered; 6-palaeosol; 7-layer with pedogenic features; 8-autochthonous peat; 9-allochthonous peat; 10-fossil burrows; 11- radiocarbon samples. EKP: Early Karginskian Palaeosol.

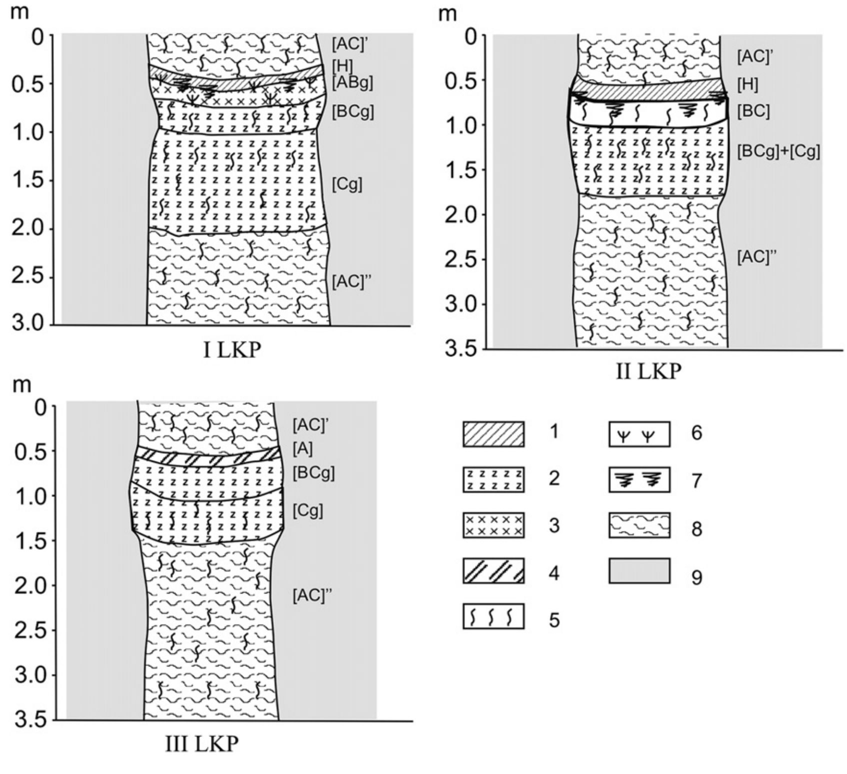

Fig. 5. Three Late-Karginskian palaeosol (LKP) profiles showing the fine structure. Nature of sediment: 1- peaty, 2- gleic, 3- peat-containing, 4-humic. Organic inclusions: 5 - thin roots, 6-wood, 7- tussocks. Units surrounding palaeosols:8 – cryopedolith, 9 - ice wedge. [AC] – cryopedoilth; palaeosol horizons – [H], [A],[ABg], [BCg], [Cg], [BC].

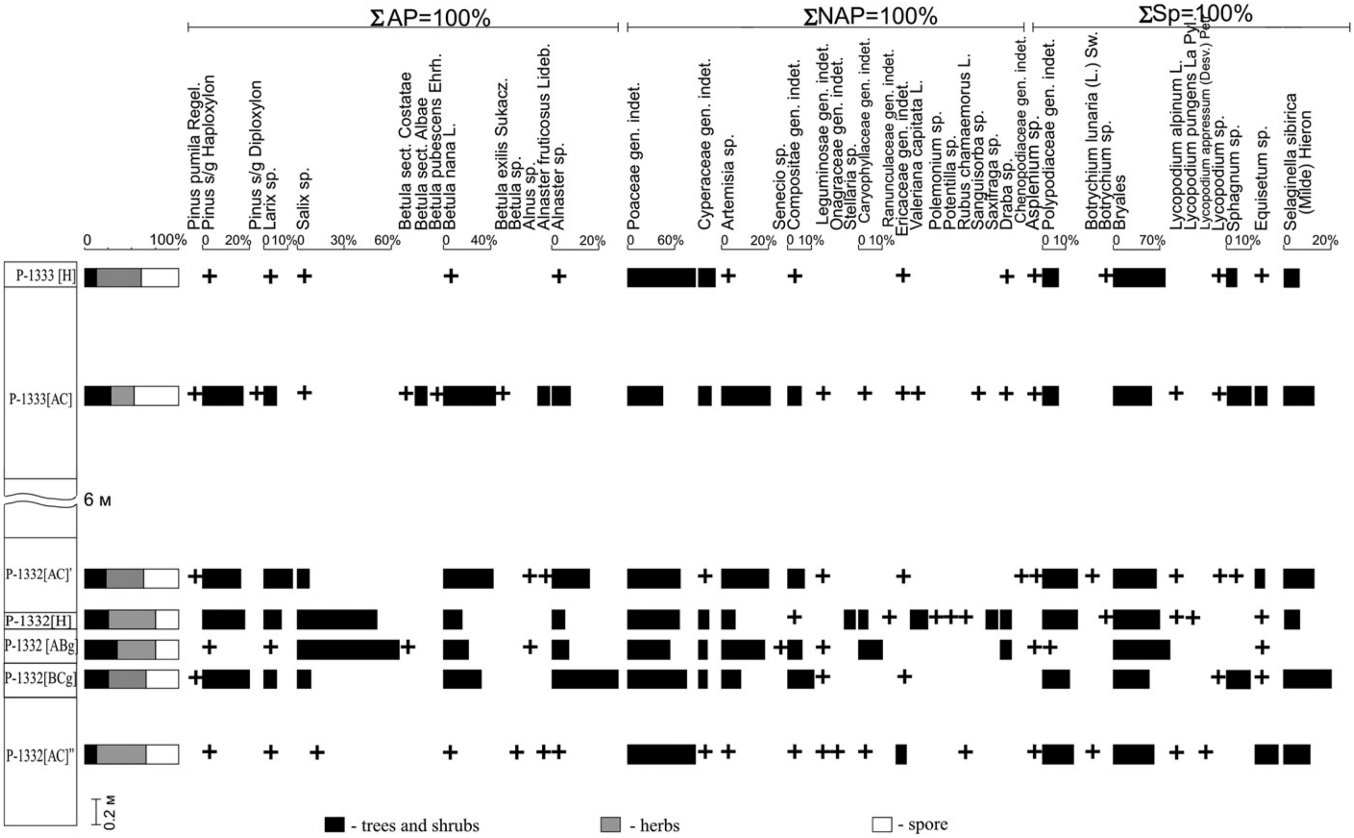

Fig. 6. Pollen diagram of the Late-Karginskian palaeosol. P-1332 LKP I; P-1333 –LKP II The vertical scale is 0.2 m. The horizontal scale 1 cm–20% where no legend. AP-arboreal, NAP-non-arboreal, Sp-sporiferous.

grades into sandy alluvial layers, peaty sandy silt, and allochthonous peat deposited in quiet-water conditions. The profile of LKP II is developed in a silty cryopedolith and is consistent across the section. The upper peaty horizon is about 15–20 cm thick and contains abundant dusty material and small tussocks with sedge and moss remains. The mineral part of the profile is gleyed and underlying horizons have significant ice content. Some profiles suggest formation under drier conditions: less intense gleization in the mineral parts of profiles, and the upper horizons have more humus. Radiocarbon ages of plant remains from II LKP are 31–33 ka B.P.

The spore-pollen spectrum of P-1333 [H] (Fig. 6) had only 24 pollen grains; these were dominated by herb pollen (mostly Poaceae); spores were also common and some dwarf shrubs (*Betula, Salix, Alnus*) were present. The spectrum probably reflects a moist tundra environment. The underlying horizon P-1333 [AC] contains more tree and shrub pollen, including tree and shrub *Betula* and *Pinus*. Poaceae and *Artemisia* dominate the herb pollen. The spectrum possibly indicates a relatively dry open forest. The plant macrofossil assemblage from the II LKP has a notable amount of *Arctous alpina* and *Betula divaricata*, and it includes the sedges *Carex concolor, C. appendiculata, C. juncella* and *Bistorta elliptica*. The plant composition from this soil suggests a sedge bog with dwarf shrubs in an open larch forest (*Betula divaricata* and *Carex juncella* are not found in tundra communities today).

The fossil beetle assemblage from the second LKP is not diverse and is dominated by the steppe-tundra beetle *Morychus viridis*. Some tundra beetles, e.g., *Pterostichus (Cryobius)* spp. and *Curtonotus alpinus*, are present, along with the water beetles, *Agabus moestus* and *Helophorus splendidus*, and *Lepyrus volgensis, which is* associated with shrub willow. Also present is the dung beetle *Aphodius* sp. The assemblage reflects a steppe-tundra environment. The water beetles overwinter in soil and thus finds of individuals are not unreasonable; their presence also indicates that small ponds or other water bodies were present in summer.

4.3.3. Late-Karginskian palaeosol III (III LKP)

This palaeosol is most prominent in the downstream part of the section. It is located from 30 to 32 m above water level. The soil is characterized by a poorly developed profile with a thickness of only 0.6–0.8 m (Fig. 5). The upper horizon includes a mixture of mineral material and poorly decomposed plant remains dominated by grasses with some moss. A gradual transition from the upper horizon to massive silt is defined by increasing silt content. The mineral part of the profile is poorly differentiated into genetic horizons and gleyed in the lower part. The soil profile has low ice content. The palaeosol is similar to dry peat or coarse Histosols found in drier sites today.

Pollen from the upper organic horizons of III LKP is dominated by Poaceae and that of dwarf shrubs, and tree and shrub pollen is low (ca 10%), reflecting a landscape of dry and/or mesic grassy communities with shrub patches, mainly dwarf birch. Some larch trees may have been present.

4.4. Inter-palaeosol deposits

The palaeosols are separated by the sedimentary unit that we term a cryopedolith. This contains a large volume of organic detritus, including plant roots, and has a layered structure. Micromorphological features showing modification of plant material and

Table 2
Beetles from palaeosols and cryopedolith MIS 3

Sample	Cryopedolith									Palaeosol			
										1		2	
	P-1216s	P-1212s	P-1321s-1	P-1321s-2	P-1219s	P-01-03s-1	P-01-03s-2	P-1311s	P-1232s	P-F1-1332s-1	P-F1-1332s-2	P-F1-1333s-1	P-F1-1333s-2
TAXON MNI													
Ord. Coleoptera													
Fam. Carabidae													
Bembidion (Plataphus) sp.	–	1	–	–	–	–	–	–	–	–	–	–	–
Poecilus (Derus) nearcticus Lth.	–	2	–	–	–	–	7	–	–	–	1	–	–
Pterostichus (Cryobius) ventricosus Esch.	–	–	–	–	–	–	–	–	–	–	2	–	–
P. (Cryobius) pinguedineus Esch.	–	–	–	–	–	–	–	–	–	6	1	–	–
P. (Cryobius) brevicornis (Kirby)	–	2	–	–	–	–	4	–	–	–	–	–	–
P. (Cryobius) spp.	–	5	–	–	–	–	1	–	1	–	–	–	6
P. (Petrophilus) abnormis Sahlb.	–	–	–	–	–	–	1	–	–	1	–	–	–
P. (Tundraphilus) sublaevis Sahlb.	–	–	–	–	–	–	–	–	–	1	–	–	–
Stereocerus haematopus Dej	–	–	–	–	–	1	–	–	–		–	–	–
Curtonotus alpinus Payk.	–	6	1	–	–	1	8	–	6	3	6	–	4
C. bokori Csiki	–	–	–	–	–	–	–	–	–	1	–	–	–
Harpalus vittatus kiselevi Kat. et Shil.	–	5	–	–	–	–	–	–	–	–	–	–	–
H. obtusus obtusus Gebl.	–	–	–	–	1	–	–	–	–	–	–	–	–
Dicheirotrichus mannerheimi Sahlb.	–	4	–	–	–	–	–	–	–	–	–	–	–
Cymindis arctica Kryzh. et Em.	–	2	–	–	–	–	1	–	–	–	1	–	–
Fam. Dytiscidae													
Agabus moestus (Curt.)	–	–	–	–	–	–	–	–	–	–	1	–	2
Fam. Hydrophilidae													
Helophorus splendidus Sahlb.	–	–	–	–	–	–	–	–	–	–	–	–	1
Fam. Leiodidae													
Cholevinus sibiricus (Jean.)	–	–	1	–	–	–	–	–	–	–	–	–	–
Fam. Staphylinidae													
Tachinus brevipennis Sahlb.	–	–	1	–	–	–	–	–	–	–	4	1	1
T. arcticus Motsch.	–	1	–	–	–	2	–	–	–	–	–	–	–
Fam. Scarabaeidae													
Aphodius sp.	–	1	1	–	–	–	1	–	–	–	3	–	2
Fam. Byrrhidae													
Morychus viridis Kuzm. et Kor.	1	46	–	–	–	–	6	1	38	2	2	12	4
Fam. Anobiidae													
Caenocara bovistae Hoffm.	–	–	–	–	–	–	–	–	–	–	1	–	–
Fam. Melyridae													
Troglocollops arcticus L.Medv.	–	–	–	–	–	–	–	–	–	–	–	1	–
Fam. Chrysomelidae													
Chrysolina arctica Medv.	–	2	–	–	–	–	–	–	1	–	–	–	–
Ch. tolli Jac.	–	–	–	1	–	–	–	–	–	–	–	–	–
Ch. subsulcata Mnnh.	–	–	–	–	–	–	–	–	1	–	–	–	–
Phratora polaris Schn.	–	–	–	–	–	–	–	–	1	–	–	–	–
Fam. Apionidae													
Mesotrichapion wrangelianum Kor.	–	–	–	–	–	–	–	–	1	–	1	–	–
Fam. Curculionidae													
Phyllobius virideaeris Laich.	–	–	–	–	–	–	1	–	–	–	–	–	–
Ph. kolymensis Kor. et Egorov	1	–	–	–	–	1	–	–	1	–	–	–	–
Coniocleonus cinerascens Hochh.	–	–	–	–	–	–	–	–	–	–	1	–	–
C. vinokurovi T.-M. et Kor.	–	–	–	–	–	–	–	–	1	–	–	–	–
C. zherichini T.-M. et Kor.	–	–	–	–	–	–	–	–	–	1	2	–	–
Coniocleonus sp.	–	–	–	–	–	–	2	–	–	–	–	–	–
Stephanocleonus eruditus Faust	–	10	–	–	–	–	4	–	3	–	–	–	–

S. fossulatus F-W.	–	–	–	–	–	–	–	–	–	1	1	–	–
Stephanocleonus sp.	2	–	–	–	–	–	–	–	1	–	–	–	–
Lepyrus nordenskieldi Faust	–	–	–	–	–	1	–	–	–	–	–	–	–
L. volgensis Fst.	–	–	–	–	–	–	–	–	–	–	–	–	1
Hypera ornata Cap.	–	2	–	–	–	–	1	–	1	–	1	–	–
H. diversipunctata Schrank.	–	–	–	–	–	–	–	–	–	–	3	–	–
Notaris bimaculatus F.	–	1	–	–	–	–	–	–	–	–	–	–	–
Isochnus arcticus Kor.	–	–	1	–	–	–	–	–	–	–	–	–	–
Ord. Heteroptera													
Fam. Pentatomidae													
Pentatomidae indet.	–	–	–	–	–	–	1	–	–	2	1	–	–
sum	4	90	5	1	1	6	38	1	56	19	32	16	21

the chemical properties of the material (SOC, forms of nitrogen, phosphorus and potassium; Table 1) indicate that pedogenic processes occurred in the active layer, accompanied by regular eolian silt influx, which led to accretion of the soil surface. Under these conditions cryogenic processes dominated; profiles are not well differentiated, biochemical activity was low, sporadic, and influenced primarily by the organic material in the upper 10–15 cm layer. The strongest influence on soil properties is the rate of eolian input to the soil surface, which in turn affected vegetation cover. As the upper surface of the permafrost rose, the lower horizons were syngenetically frozen. This process led to exceptional preservation of organic remains. Most of the ice complex deposits of MIS-2 and MIS-3 of the Duvanny Yar exposure can be classified as cryopedoliths.

4.5. *Rodent burrows*

This unit contains an important source of palaeoenvironmental information in the form of fossil rodent burrows. The storage of plant and animal remains in these burrows provides a record of the surface biota that includes rare seeds and insects that are uncommon in the surrounding sediment. Large chambers of some burrows contain up to 800,000 seeds and fruits (Gubin and Khasanov, 1996); however, more often, there are tens of thousands of specimens (per 50–100 g of dry weight). We have found more than 30 rodent burrows in this unit of the Duvanny Yar exposure.

4.5.1. *Plant macrofossil record from the burrows*

The plant macrofossil assemblages contain 48 plant taxa assignable to various ecological groups (Table 3). The data indicate a mosaic of vegetation cover. The most common vegetation type is an open larch woodland with four communities: 1) upland open woodland with *Betula divaricata*; 2) floodplains, poorly-drained bottoms and alasses; 3) pioneer communities of disturbed habitats (thermo-erosional ground mound and river bank slopes); 4) and steppe communities on south-facing slopes. These habitats differed significantly in their available moisture.

The vegetation of the open larch woodlands includes larch trees - *Larix cajanderi;* shrubs - *Betula divaricata;* dwarf shrubs—*Arctous alpina, Vaccinium uliginosum;* and herbs—*Bromopsis pumpelliana, Poa alpigena, Alopecurus alpinus, Hedisarum arcticum* and the moss *Aulacomnium turgidum*. These plants grew in the tundra and in open woodlands, except larch, which is a typical tree of the Siberian northern boreal forest. The presence of larch seeds is important. Traditional reconstructions, based on pollen, often do not record larch since the pollen grains are poorly preserved. In contrast, *Potentilla nivea* is an indicator of dry tundra and rocky slopes with a steppe association. *Poa attenuata, Silene stenophylla, Silene repens, Elytrygia villosa,* and *Lychnis sibirica* are widespread steppe plants also occurring today. Vegetation of poorly-drained valleys is indicated by *Carex concolor, Polemonium acutiflorum, Bistorta vivipara*, all typical of the area today. Pioneer plants typical of eroding silt deposits or fresh alluvium include *Sisymbrium polymorphum, Plantago canescens,* and *Tanacetum vulgare. Ranunculus repens* and *Rumex arcticus* indicate moist habitats and occur today on river banks. *Puccinella hauptiana* is occurs in moist saline meadows.

4.5.2. *Palynology of the burrows and enclosing sediments*

Herb pollen is dominant in the MIS-3 cryopedolith unit, while spores and tree and shrub pollen are less common. Five pollen spectra from burrows and coprolites are shown in Fig. 8. Other pollen spectra from sediment samples taken close to fossil burrows show a similar composition (Lopatina and Zanina, 2006). Assemblages are dominated by herbaceous taxa, including *Artemisia* and Caryophyllaceae. Tree and shrub pollen include *Pinus s/g Haploxylon*,

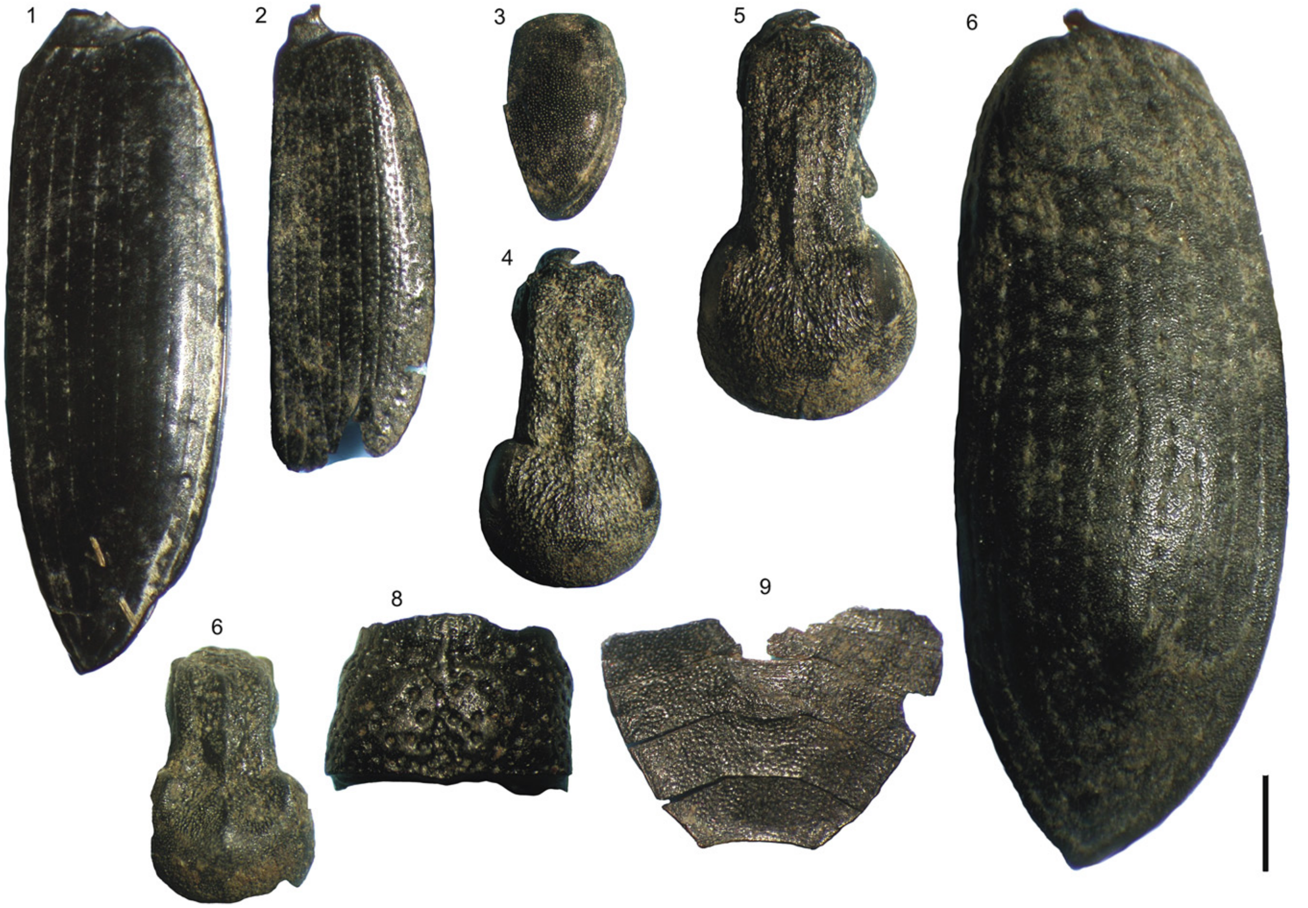

Fig. 7. Fossil insects from the palaeosol, sample P-F1,2,: 1 - *Poecilus (Derus) nearcticus,* elytron; 2 - *Cymindis arctica,* elytron; 3 - *Caenocara bovistae*, elytron; 4 – *Coniocleonus cinerascens*, head; 5,6 – *C. zherichini*, head, elytron; 7,8 - *Stephanocleonus fossulatus*, head, pronotum; 9 - Pentatomidae gen. indet., abdomen. The scale bar is 1 mm.

Pinus s/g Diploxylon, Betula nana and *Alnaster.* The maximum content of arboreal pollen is about 26%, though it is often less. Spores contribute up to 40% of the total, dominated by Bryales, Polypodiaceae and *Selaginella sibirica* Sphagnaceae, Equisetaseae and Lycopodiaceae spores occur sporadically.

The pollen data suggest an open grass and grass-herbaceous assemblage characterized by Asteraceae, Caryophyllaceae, and Fabaceae, probably moss-grass tundra. Xerophilous plant communities with *Artemisia,* Poaceae and Asteraceae occurred on dry slopes, and *Salix* spp. *Alnaster fruticosus*, *Betula nana*, sedges and mosses occurred in more mesic sites. These assemblages are similar to those of the present.

4.5.3. *Insects from the burrows and adjacent sediments*

Fossil insects were studied from 16 rodent burrows and 9 screened samples from the cryopedolith. Fossil insects from the burrows are not abundant, and mostly represented by single remains. The maximum number of individuals is 18 (Table 4). Most fossils belong to the dung beetle *Aphodius* sp. (Fig. 9), and most of these remains have very good preservation: connected head and pronotum, whole body with part of the legs, etc. This preservation is rare in fossil studies since even modern beetle specimens can easily lose body parts during preparation. This level of preservation is clear evidence that the beetle had lived in the burrow just before death. Probably this species was connected with ground-squirrel nests in the Pleistocene. We have examined the collections of the Zoological Museum in St. Petersburg and have not found any similar modern species. It appears most likely that this *Aphodius* represent an extinct Pleistocene species (or it belongs to some still undescribed modern one). This sort of habitat is associated with some species of *Aphodius* dung beetles. A number of species have been described from burrows and reported as obligate commensals of rodents (Hubbell and Goff, 1939; Skelly and Woodruff, 1991).

Other beetles are represented by single remains; their preservation is good, but not extraordinary. There are tundra species such as the ground beetles *Pterostichus (Cryobius)* sp., *Curtonotus alpinus, Dicheirotrichus mannerheimi*, and the leaf beetle *Chrysolina septentrionalis*, but most beetles from the fossil burrows are steppe-tundra indicators, including the pill beetle *Morychus viridis* and the weevil *Stephanocleonus eruditus*. These beetles did not live in the burrows, but they could use the holes as shelter, or they may have been collected by ground squirrels for food. With the exception of the high proportion of *Aphodius* specimens, the fossil insect list is typical of the steppe-tundra insect community. Fossil insects are more numerous from the screened sediment samples (Table 2). All insect assemblages are dominated by steppe-tundra indicators: the pill beetle *Morychus viridis,* the weevils *Stephanocleonus eruditus, S. fossulatus, Coniocleonus cinerascens, C. zherichini*, and the ground beetles *Cymindis arctica, Harpalus vittatus kiselevi, H. obtusus obtusus*. Some of the screened samples are relatively poor in insect remains (P-1321s-1, 2; P-01-03s-1) and include only tundra and meadow species, including high-arctic species such as the leaf beetle *Chrysolina tolli* and the weevil *Isochnus arcticus*. A low concentration of beetle fossils and a lack of steppe elements likely reflects a more severe environment, but the evidence for this is

Table 3
List of determined plant macrofossil from sediments and rodent burrows Duvanny Yar (MIS-3).

Taxon	Sample ID	1	1071	1072	1075	1212	1212	1219	1311	1311	1320	1321	01–03	01–03	Habitat
	Origin of samples	Burrow	Burrow	Burrow	Burrow	Burrow	Cryopedolith	Burrow	Burrow	Channel of burrow	Burrow	Cryopedolith	Burrow	Cryopedolith	
	Plant part														
Allium strictum Schrad.	Seeds	–	–	–	+	–	–	–	–	–	–	–	–	–	Steppe
Arctophila fulva (Trin.) Anderss.	Seeds	–	–	–	–	+	–	–	–	–	–	–	–	–	Shallow water, silt substrate
Arctous alpina (L.) Niedenzu	Seeds	+	–	–	–	+	+	–	–	+	–	–	+	+	Sparse larch forests
Astragalus alpinus L.	Seeds	–	–	–	–	–	–	–	+	+	+	–	–	–	Sparse larch forests
Bistorta vivipara (L.) S.F.Gray	Stem bulbs	–	–	–	–	+	–	+	+	+	+	–	+	–	Valley mires
B. elliptica (Willd. ex Spreng.) Kom.	Seeds	–	–	–	–	–	+	–	–	–	–	–	–	+	Sparse larch forests
Calamagrostis purpurascens R. Br.	Seeds	–	–	–	–	+	–	–	–	–	–	–	–	–	Steppe
Carex appendiculata (Trautv. et C.A.Mey.) Kük.	Seeds	–	–	–	–	–	–	–	–	–	–	+	–	+	Mire
C. aterrima Hoppe	Seeds	–	–	–	–	–	–	–	–	–	–	–	–	+	Mire
C. atrofusca Schkuhr	Seeds	–	–	–	–	–	–	–	–	+	–	–	–	–	Mire
C. bonanzensis Britt.	Seeds	–	–	–	–	–	–	–	+	–	–	–	–	–	Mire
C. concolor R.Br.	Seeds	+	–	–	–	–	+	+	–	+	–	+	+	+-	Mire
C. duriuscula C.A.Mey.	Seeds	–	–	–	–	–	–	–	–	–	–	–	+	–	Steppe
C. juncella (Fries) Th.Fries	Seeds	–	–	–	–	–	–	–	–	–	–	+	–	–	Swampy meadow
C. misandra R.Br.	Seeds	–	–	–	–	–	–	–	–	+	–	–	–	–	Mire
C. pallida C.A.Mey.	Seeds	–	–	–	–	–	–	+	–	–	–	–	–	–	Mire
C. saxatilis L.	Seeds	–	–	–	–	–	–	–	–	+	–	–	–	–	Mire
C. vesicata Meinsh.	Seeds	–	–	–	–	–	–	–	+	–	–	–	–	–	Mire with standing water
Chenopodium album L.	Seeds	–	–	–	+	–	–	–	–	–	–	–	–	–	Disturbed habitats
Ch. prostratum Bunge	Seeds	+	–	–	–	–	–	–	–	–	–	–	–	–	Disturbed habitats
Gentianopsis barbata (Froel.) Ma	Fruits, seeds	–	–	–	–	–	–	–	–	–	+	–	–	–	Sparse larch forests
Hedysarum arcticum V.Fedtsch.	Seeds, fruits	–	+	+	–	–	–	–	–	–	–	–	–	–	Sparse larch forests
Hordeum jubatum L.	Seeds	–	–	–	–	–	–	–	–	+	–	–	–	–	Disturbed habitats
H. brevisubulatum (Trin.) Link	Ear	–	–	+	–	–	–	–	–	–	–	–	–	–	Meadows (low salinity)
Larix cajanderi Mayr	Twigs	–	–	–	–	–	–	–	–	+	–	–	–	+	Sparse larch forests
Lychnis sibirica L.	Seeds, pods	–	+	+	+	–	–	–	–	–	–	–	–	–	Steppe
Pedicularis kolymensis A.Khokhr.	Seeds	–	–	–	–	–	–	–	–	–	+	–	–	–	Valley mire
Plantago canescens Adams	Fruits, seeds	–	+	+	+	–	–	+	–	–	–	–	–	–	Disturbed habitats
Poa attenuata Trin.	Seeds	–	+	+	+	–	–	–	–	–	–	–	–	–	Steppe
P. botryoides (Trin. ex Griseb.) Kom.	Seeds	–	+	+	+	–	–	–	–	–	–	–	+	–	Steppe
Potentilla stipularis L.	Seeds	–	–	–	+	–	+	–	–	–	–	–	+	–	Disturbed habitats
Polemonium acutiflorum Willd. ex Roem. et Schult.	Fruits, seeds	–	–	+	–	–	–	–	–	–	+	–	+	–	Valley mire
Potentilla nivea L.	Seeds	+	+	+	–	+	–	+	+	+	+	–	–	–	Sparse larch forests
Puccinella hauptiana V.Krecz.	Seeds	+	–	–	–	+	+	–	–	–	–	–	–	–	Meadow (low salinity)
Ranunculus repens L.	Seeds	–	–	–	–	–	–	–	–	–	–	–	+	–	Valley mire
Rhodiola rosea L.	Seeds	–	–	–	–	–	–	–	–	–	+	–	–	–	Sparse larch forests, stony slopes
Rumex arcticus Trautv.	Seeds	–	+	+	+	–	–	–	–	+	–	+	–	–	Valley mire
Salix sp.sp.	Fragments of branchs	–	–	–	–	–	+	–	–	+	+	+	–	+	Thin larch forests and valley mire
Salix glauca L.	Fruits	–	–	–	–	–	–	–	–	+	–	–	–	–	Sparse larch forests
Sanguisorba officinalis L.	Seeds	–	–	+	–	–	–	–	–	+	–	–	–	–	Valley mire
Silene stenophylla Ledeb.	Seeds, pods	–	+	+	+	+	–	+	–	–	+	–	+	–	Steppe
Sisymbrium polymorphum (Murr.) Roth	Seeds, pods	+	–	–	+	+	–	–	–	–	+	–	+	–	Disturbed habitats
Taraxacum lateritum Dahlst.	Seed	–	–	–	–	–	–	–	–	–	–	–	+	–	Disturbed habitats
T. macilentum Dahlst.	Seeds	–	–	–	+	–	–	–	–	–	–	–	–	–	Disturbed habitats
Mosses															
Aulacomnium palustre *(Hedw.) Schwaegr.*	Vegetative parts	–	–	–	–	–	–	–	–	+	+	–	–	–	Sparse larch forests
Bryum arcticum *(R.Brown) B.S.G.*	Vegetative parts	–	–	–	–	–	–	–	–	+	–	–	–	–	Sparse larch forests
Total of species	–	6	8	11	10	8	6	6	5	16	11	5	11	7	–

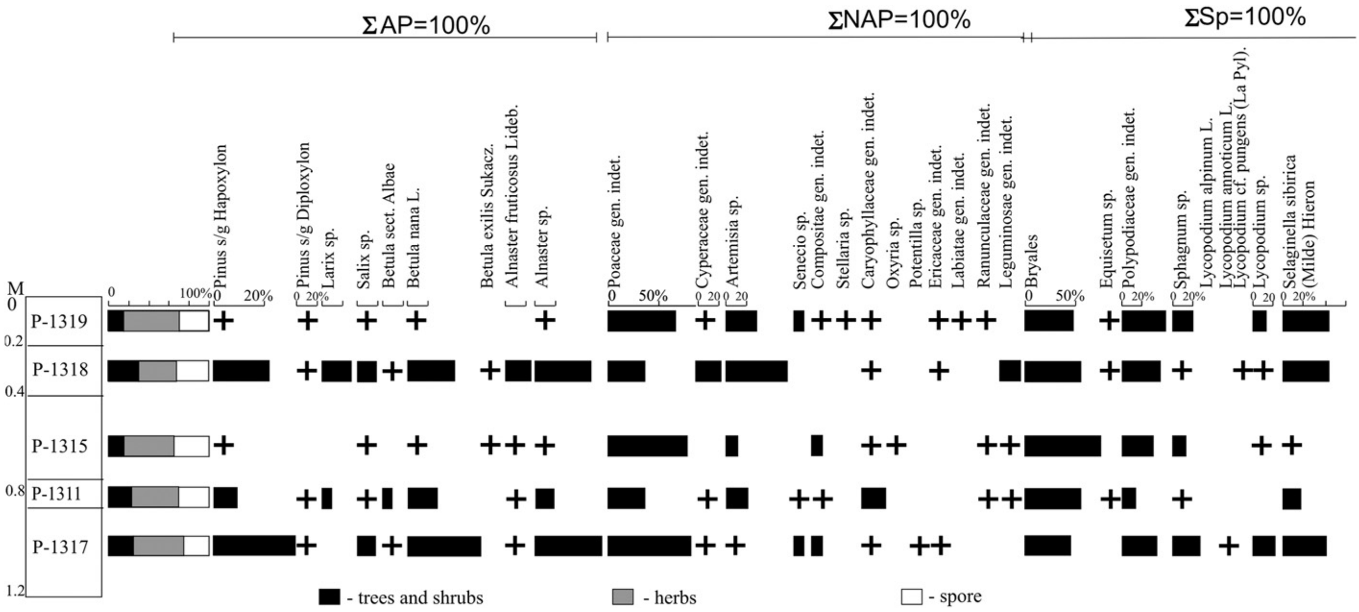

Fig. 8. Five pollen spectra from burrows and coprolites dating to MIS-3. The horizontal scale bar is 20% where no legend. AP-arboreal, NAP-not arboreal, Sp-sporiferous.

equivocal since the assemblages are so small. There are no forest indicators in any of the studied insect samples.

4.6. MIS-2 unit

The MIS-2 unit has a thickness of about 25 m, and overlies the first buried soil profile (Figs. 3 and 4). The material is a bluish-grey silty loam (10YR5/1) with a microlenticular cryostructure. It has a coarsely layered structure, the thickness of each layer being about 0.8–3 (up to 6) meters. Layers differ by color intensity, and contain strongly mineralized thin grass roots *in situ*. There are no consistent differences in colour, grain-size distribution, root abundance or cryotexture between layers. Coarse (0.05–0.01 mm) and medium (0.01–0.05 mm) silt fractions dominate the majority of layers. The proportions of coarse and medium silt fractions change slightly near the borders between layers.

Microscopic plant fossils of 0.01–0.1 mm (detritus) are also present in these layers. Micromorphological study shows that they appear to be small parts of sedge and grass vegetation; fossils of mosses occur but are rarer. Detritus is uniformly distributed in the mineral material. Plant fossils are strongly mineralized, discolored or ferruginous. Humified fossils are rarely found (Fig. 10). Plant detritus mainly determines the soil organic carbon (SOC) content in the studied layers of ice complex (Table 4). SOC content varies in MIS-2 deposits between 0.6 and 1.8% (by average = 1.2%, $n = 45$). C:N index is 8:9, ignition losses are about 5–8%. These data confirm the main role of detritus in forming the organic material of the deposits. The ranges of SOC are similar to those of material comprising baidzherakhs (residual ground mounds). The main chemical properties are fairly consistent: pH 7.5–7.7 and carbonate content about 0.3–0. Grain-size distribution and ice content indexes are also consistent. The ferrous oxide index and rate of readily soluble forms of phosphorus and potassium differ more significantly, and are apparently linked with SOC content.

One of the significant facts that is not well understood today is the high concentration of mobile forms of phosphorus in the ice complex deposits. It may reach 80 mg per 100 g 32 mg per 100 g by average ($n = 28$) while the total index does not exceed 0.2%. This was first recognized by Zhigotsky (1982), who linked it to unusual pedogenic processes of Late-Pleistocene tundra-steppe of ancient Beringia. We connect such high indices with the detritus content and structure of the material, the shallow ancient active layer (not more than 0.8 m), the absence of well-expressed relief, and aridity. All of these factors prevent the removal of mobile biophylic elements from the soil profile and limit their spatial redistribution.

4.6.1. Palaeoecology of MIS-2 unit

All MIS-2 pollen samples are dominated by spores, most commonly *Equisetum*. *Selaginella rupestris* and green mosses are also abundant. In the grasses and herbs group, tree and shrub pollen is represented by sporadic *Larix*, *Haploxylon* and *Betula* sp. pollen; Poaceae is dominant; while Cyperaceae and various herbs are also abundant.

Macrofossils from fossil rodent burrows indicate the region presence of tundra communities (*Potentilla nivea, Vaccinium minus, Dryas octopetala* subsp. *subincisa, Salix Polaris;* mosses *Aulacomnium palustre var. imbricatum* and *Polytrichum hyperboreum;* lichens *Cetraria cucullata, Cetraria laevigata* and *Peltigera aphtosa*). The pioneer associations indicate a disturbed habitat (*Plantago canescens, Taraxacum lateritum*) and steppe associations may have occurred on south- facing slopes, indicated by *Allium strictum* and *Poa botryoides*, for example.

The beetle records (Kaplina et al., 1978; Kiselev, 1981) also show a well developed steppe-tundra environment. The pill beetle *Morychus viridis* is most common, while steppe and meadow-steppe species such as the weevils of *Stephanocleonus* genus and true bug *Aelia frigida* are also important components.

5. Discussion

We have recognized and described four epigenetic palaeosols in the MIS-3 part of the Duvanny Yar section. Research in other regions of northeast Asia also records buried soils in MIS-3 deposits and their absence in MIS-2. Exposures of early Karginskian palaeosols (>40 ka BP) are uncommon due to their landscape position close to the modern river level. At Duvanny Yar this period is represented by peat (allochthonous and autochthonous), a peaty soil profile, or in some exposures by alluvial or lacustrine deposits.

Table 4
Beetles from fossil burrows.

Sample	B-Dyb	P-1212b-1	P-1212b-2	P-1212b-3	P-1213b	P-1321b-1	P-1321b-2	P-1075b-1	P-1075b-2	P-1334b	P-1335b	P-1311b-1	P-1311b-2	P-1326b	P-1325b	P-01-03-2003b
TAXON MNI																
Ord. Coleoptera																
Fam. Carabidae																
Pterostichus (Cryobius) brevicornis (Kirby)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1
Pterostichus (Cryobius) sp.	–	–	–	–	–	1	–	1	–	–	–	–	–	–	–	–
Curtonotus alpinus Payk.	–	1	–	1	–	–	–	–	–	–	–	–	–	–	1	–
Harpalus vittatus kiselevi Kat. et Shil.	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–
Dicheirotrichus mannerheimi Sahlb.	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–
Cymindis arctica Kryzh. et Em.	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–
Fam. Scarabaeidae	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Aphodius sp.	–	–	–	–	–	3	1	–	–	–	1	14	4	–	17	–
Fam. Byrrhidae	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Morychus viridis Kuzm. et Kor.	1	–	–	–	1	–	–	–	–	–	–	–	–	1	–	1
Fam. Chrysomelidae	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Chrysolina brunnicornis bermani Medv.	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–
Ch. septentrionalis Men	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–
Fam. Curculionidae	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Phyllobius virideaeris Laich.	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–
Ph. kolymensis Kor. et Egorov	–	–	–	–	–	–	–	–	–	–	4	–	–	–	–	–
Coniocleonus sp. ?	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–
Stephanocleonus eruditus Faust	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–
Stephanocleonus sp.	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–
Ord. Diptera	–	–	–	–	–	+	–	+	–	+	–	–	–	–	–	–
Ord. Lepidoptera	–	–	–	–	–	–	+	–	–	–	–	–	–	–	–	–
Ord. Hymenoptera	–	–	–	–	–	–	–	–	–	–	–	–	–	–	+	–
sum	1	1	1	8	1	4	1	1	1		7	14	4	2	18	2

Fig. 9. Fossil insects from a burrow, Sample P-1325b. The remains are of *Aphodius* sp. and feature different part of the body: wings, legs and soft issue.

The early stages of Karginskian pedogenesis are characterized by forest soils, including large woody macrofossils and course humus with leaves. The lack of a mineral component suggests that eolian inputs to the Karginskian soil were minimal.

Features of late MIS-3 (~40–26 ka BP) palaeosols vary. At many sites along large river valleys (e.g., the Yana, Indigirka, and Vilyuy rivers) the dominant deposits are alluvium, and only poorly developed alluvial soils or peaty layers are present. Duvanny Yar soils of this period are not alluvial but rather peaty-bog soils and peaty-gleyed soils. The presence of a mineral fraction within the organic horizons suggests some accumulation of the mineral sediment, albeit discontinuous, during periods of epigenetic soil formation. Buried sedge tussocks indicate significant moisture during the early stages of pedogenesis. A possible interpretation is that soil formation was related to local warming, during which melting of the upper parts of ice wedge polygons provided additional moisture. Subsequent soil formation took the form of peat aggradation with some eolian silt accumulation, burying the tussocks. At the same time, rising permafrost resulted in peat accumulation above the polygonal depressions. If the small-scale soil mosaic depended upon its location relative to the polygonal ground network, this would explain the presence of "cold" elements in the pollen spectra in the buried soils, whereas the combination of xerophilous and meso-hygrophilus plant and insect taxa could reflect the broader mosaic.

Chemical characteristics of the buried soils reflect slow soil formation processes and a short period of pedogenesis. Soils of the latest MIS-3 period are characterized by the increasing of importance of lithogenesis and of cryoxeric conditions. Epigenetic soil processes were eventually replaced by synlithogenetic ones toward the top of this unit, likely reflecting a cooling trend toward the end of MIS-3.

Between palaeosls and during MIS-2 synlithogenic processes dominate. This indicates a severe environment, likely cold and dry, with fairly constant silt deposition. Cryopedoliths from MIS-3 and MIS-2 are similar in macro-morphological structure, chemical composition and grain size, but they differ in their microstructure. The MIS-3 cryopedolith is characterized by greater micro-aggregation of sediment inclusions under relatively humid conditions. Generally higher humification and incorporation of humus in micro-aggregations could also reflect warmer summer temperatures. Furthermore, MIS-3 cryopedolith layers contain more diverse plant remains, such as above ground and underground parts of sedges, grasses and mosses. In contrast, the MIS-2 sediment contains mainly grass remains and mosses are rare. These data suggest that conditions may generally have been warmer and moister in MIS-3 compared with MIS-2, even during periods of silt accumulation. The alternation of cryopedoliths and epigenetic soils within MIS-3 may, therefore, reflect local landscape heterogeneity or regional climate variations; accurate dating of the palaeosols across the widely distributed MIS-3 sites in northeast Asia may lend support to the latter hypothesis. To date, this has been difficult to achieve with radiocarbon as the period in question is near the limit of reliable dating.

Pollen spectra from MIS-3 cryopedolith beds are similar in their major details, such as proportions of the main functional groups (trees, shrubs, herbs, crytogams), and they have low species diversity. Shrub pollen dominates and tree pollen is from a single taxon—*Larix* (*Pinus* pollen is predominantly of the shrub pine, *P. pumila*). Poaceae dominates the grass-herbaceous group, up to 80% in some samples, with *Artemisia* variable and sometimes important. Plant macrofossils of *Larix*, together with representatives of open larch forest communities such as the sedges *Carex atterima* and *C. juncella,* confirm the local presence of larch trees, while other plant taxa indicate pioneer and steppe habitats.

Thus soil properties and plant fossil assemblages are fairly consistent in portraying relatively mesic conditions and a landscape that includes a mosaic of habitats from locally dry and disturbed substrates to more mesic habitats supporting woody vegetation that included *Larix*.

In contrast, fossil insects indicate a steppe-tundra environment, and they do not indicate forest vegetation. Larch forest near its northern limits today is sparse or discontinuous and trees are small. Such a poorly developed forest community is a challenge to reconstruct from the insect fossil records, as demonstrated by the fact that modern insect assemblages collected from the northernmost larch forest (near Chersky by S.Kuzmina) look more similar to tundra assemblages and contain very few forest species. Given the possible loss of rare specimens through taphonomic processes, the fossil insect record may lack the forest indicators, while the remains of the trees themselves are more likely to be recorded as macrofossils. In this regard, the insect and pollen records of *Larix* are similar, as *Larix* produces relatively little pollen that is poorly preserved.

The abundant fossil burrows of the ground squirrel *Spermophylus parryi* (Rich.) provide an exciting new window on past environments, particularly because of the large volume of fresh seeds preserved in them, which is due to the foraging behaviour of the ground squirrels, which store the seeds near the permafrost. The syngenetic nature of the permafrost means the seeds are rapidly frozen if not utilised. The seeds thus promise to be excellent material for studies of ancient DNA. Furthermore, some seed tissue is still viable and has been successfully cultured along with moss spores (Yashina et al., 2002). The burrows thus can contribute to investigations of fundamental biological processes such as evolution and long-term cryopreservation.

Fossil burrows in permafrost are described not only from Duvanny Yar, but also from eastern Beringia (Guthrie, 1990; Harington, 1984; Zazula et al., 2003, 2005). In contrast to those in Siberia, they are described mostly from "cold" stage deposits such as MIS-2. This difference in ground-squirrel preferences could be explained in two ways: first, the ground squirrels belong to different subspecies and may have different ecological preferences; second, the MIS-2 environment of far-eastern Beringia differed significantly from that of the Kolyma Lowland. While these are not mutually exclusive, the weight of evidence suggests different behaviours and/or biogeographic constraints, rather than greatly differing environments; further comparative studies of the Asian and North American ground squirrels may shed further light on these differences.

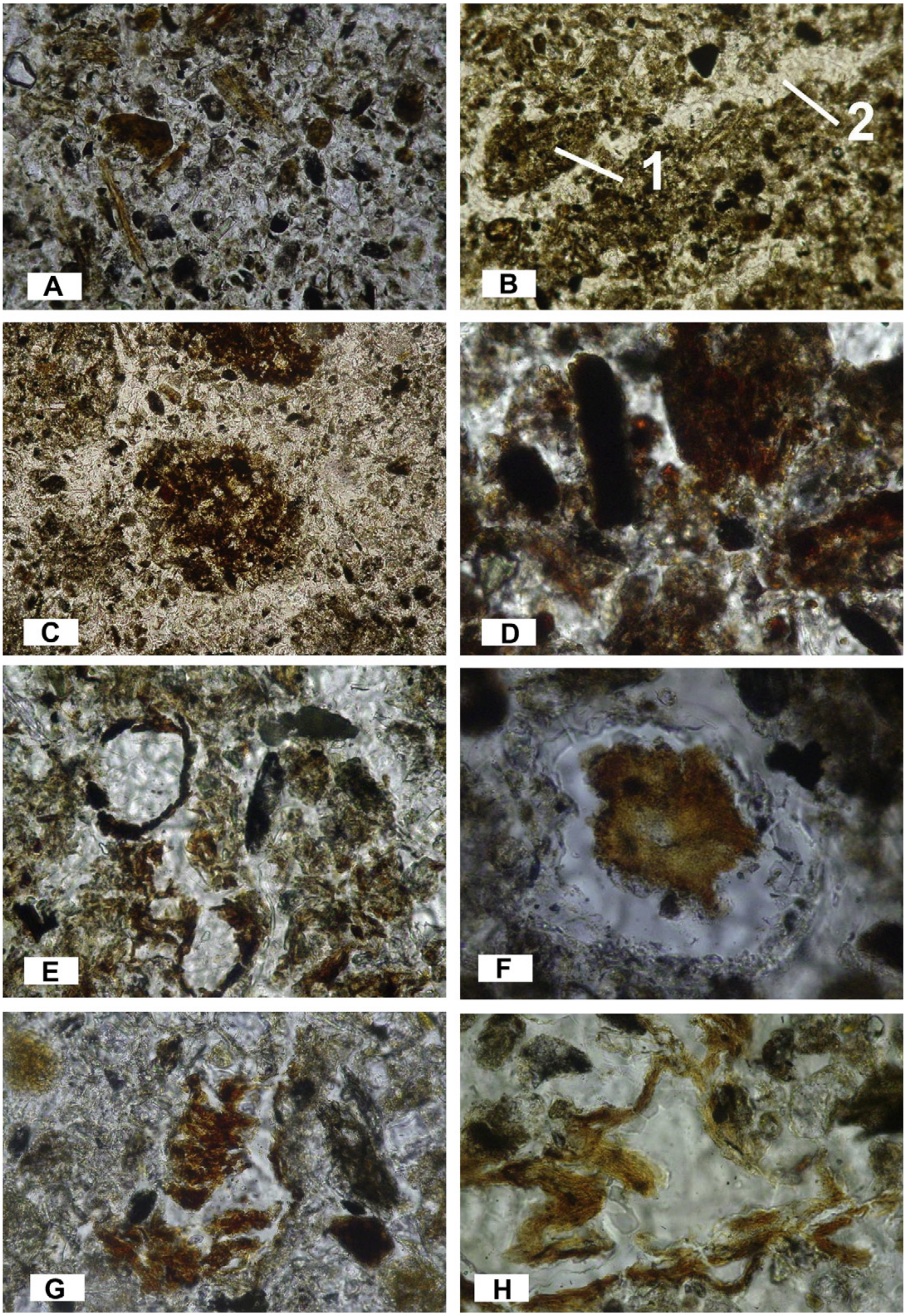

Fig. 10. Micromophological structure of MIS-3 cryopedolith: A - general microstructure of cryopedolith MIS-3; B: 1- soil microaggregate, 2- microtexture, remaining after thawing of microschlieren ice; C - the structure of an individual microaggregate; D - mineralized and humified organic remains in cryopedolith matter; E– mineralized root remains; D- root remains *in situ*; G- moss fragments; H- herbaceous plant fragments.

6. Conclusions

Detailed studies of soil genesis, micromorphology, and fossils of MIS-3 and MIS-2 deposits at Duvanny Yar reveal considerable information about local conditions and landscape mosaics, as well as regional climate changes. Such detail is seldom achieved in palaeoenvironmental studies of yedoma deposits but can yield fruitful results. Seeds retrieved from ground-squirrel burrows enhance the fossil record and their excellent preservation opens up new avenues of research in palaeobiology and cryobiology.

The wide lateral extent of the high frozen bluffs at Duvanny Yar is exceptional, and the locality deserves regular study as the exposures are continually changing and revealing new material.

Acknowledgements

This study was supported by the Russian Foundation for Basic Research (projects № 01-04-49087, 04-05-64748, 08-04-00597, 08-04-00130). We thank Galina Alexandrova for assistance in sample treatment. Lubov Shmakova assisted with figure preparation. Many thanks to Leopold Sulerzhitsky for radiocarbon dating of samples. We also appreciate assistance in field trips by Alexander Skotnikov and his permanent interest in this work. We are grateful to our colleagues in North–East Scientific Station, Pacific Institute for Geography, Far-East Branch Russian Academy of Sciences, in Chersky, Republic of Sakha (Yakutia) for their help, cooperation, and useful discussions.

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